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(54) METERLESS HYDRAULIC SYSTEM HAVING MULTI-ACTUATOR CIRCUIT

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CPC ***E02F 9/2296*** (2013.01); ***E02F 9/2217*** (2013.01); ***E02F 9/2235*** (2013.01); ***E02F 9/2289*** (2013.01); *F15B 7/006* (2013.01); ***F15B 11/036*** (2013.01); ***F15B 11/0423*** (2013.01); *F15B 15/221* (2013.01); *F15B 2211/20546* (2013.01); *F15B 2211/20561* (2013.01); *F15B 2211/20569* (2013.01); *F15B 2211/212* (2013.01); *F15B 2211/27* (2013.01); *F15B 2211/30565* (2013.01); *F15B 2211/30595* (2013.01); *F15B 2211/31529* (2013.01); *F15B 2211/31541* (2013.01); *F15B 2211/40592* (2013.01); *F15B 2211/41563* (2013.01); *F15B 2211/50527* (2013.01); *F15B 2211/613* (2013.01); *F15B 2211/625* (2013.01); *F15B 2211/6346* (2013.01); *F15B 2211/6654* (2013.01); *F15B 2211/7055* (2013.01); *F15B 2211/7128* (2013.01); *F15B 2211/7135* (2013.01); *F15B 2211/7142* (2013.01); *F15B 2211/761* (2013.01); *F15B 2211/763* (2013.01); *F15B 2211/785* (2013.01); *F15B 2211/88* (2013.01); ***E02F 9/2285*** (2013.01)

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USPC 60/413, 414, 420, 445, 459, 473, 475, 60/476, 484
See application file for complete search history.

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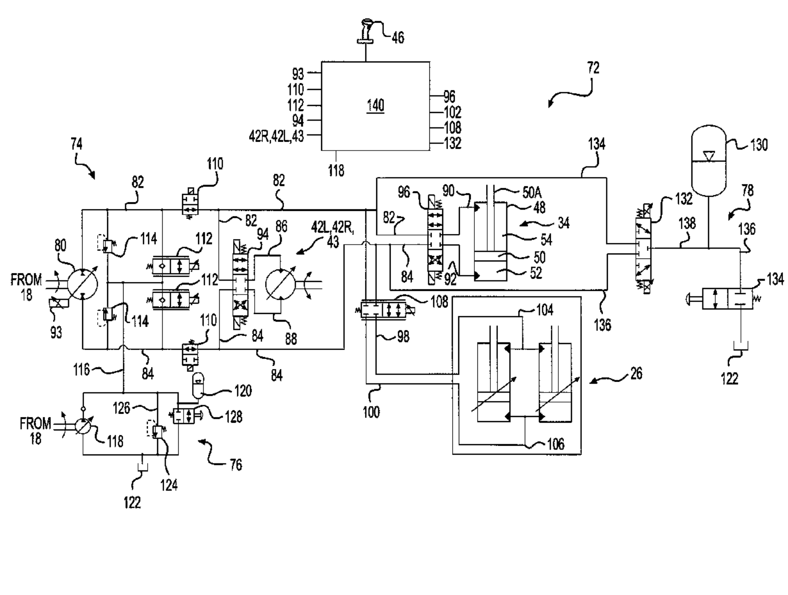
(57) **ABSTRACT**

A hydraulic system is disclosed. The hydraulic system may have a pump, a first actuator, and a meterless circuit connecting the first actuator to the pump. The hydraulic system may also have a second actuator connected to the meterless circuit in parallel with the first actuator. The second actuator may be a variable-area linear actuator.

15 Claims, 3 Drawing Sheets



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F15B 7/00	(2006.01)
F15B 15/22	(2006.01)

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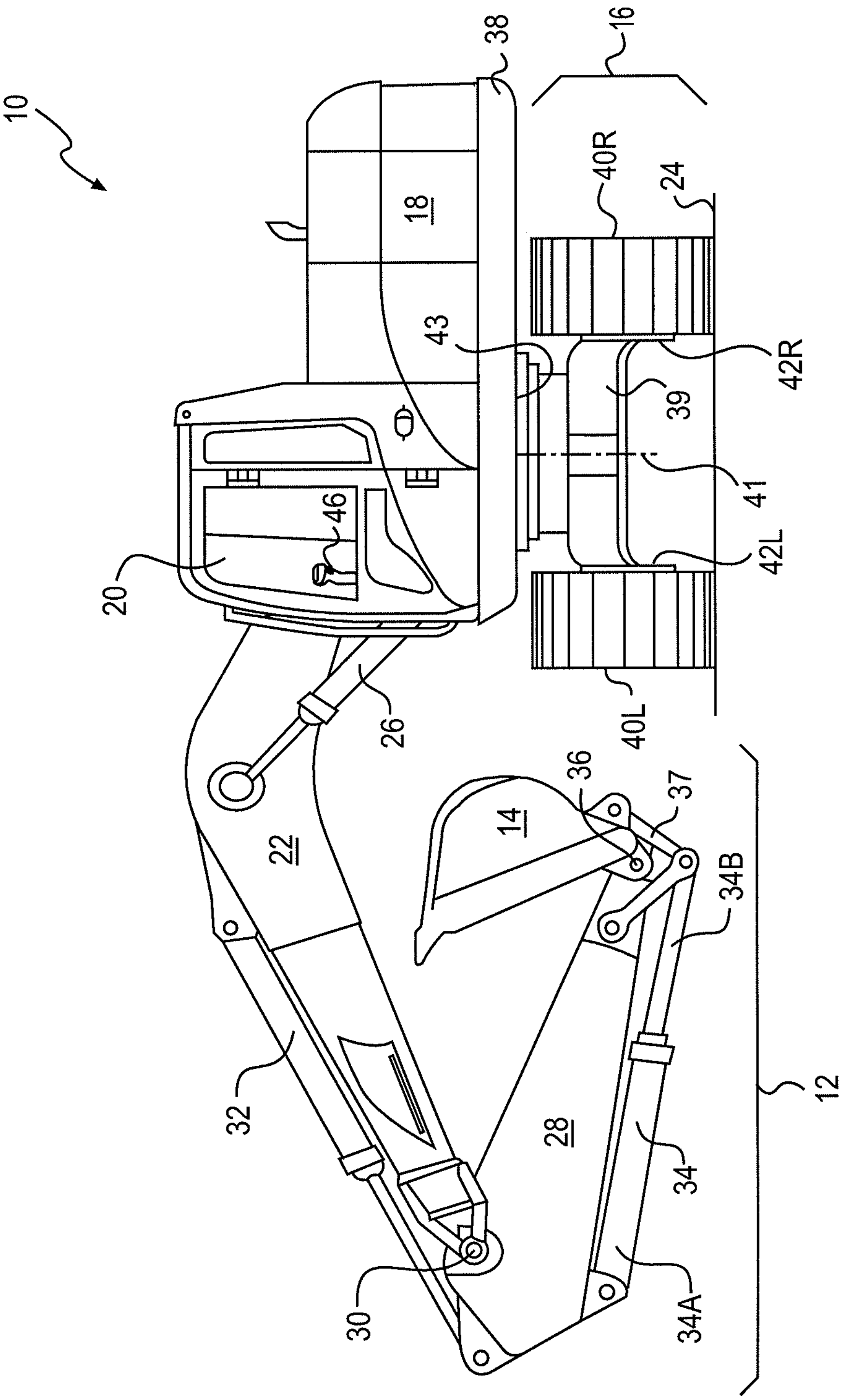
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FIG. 1

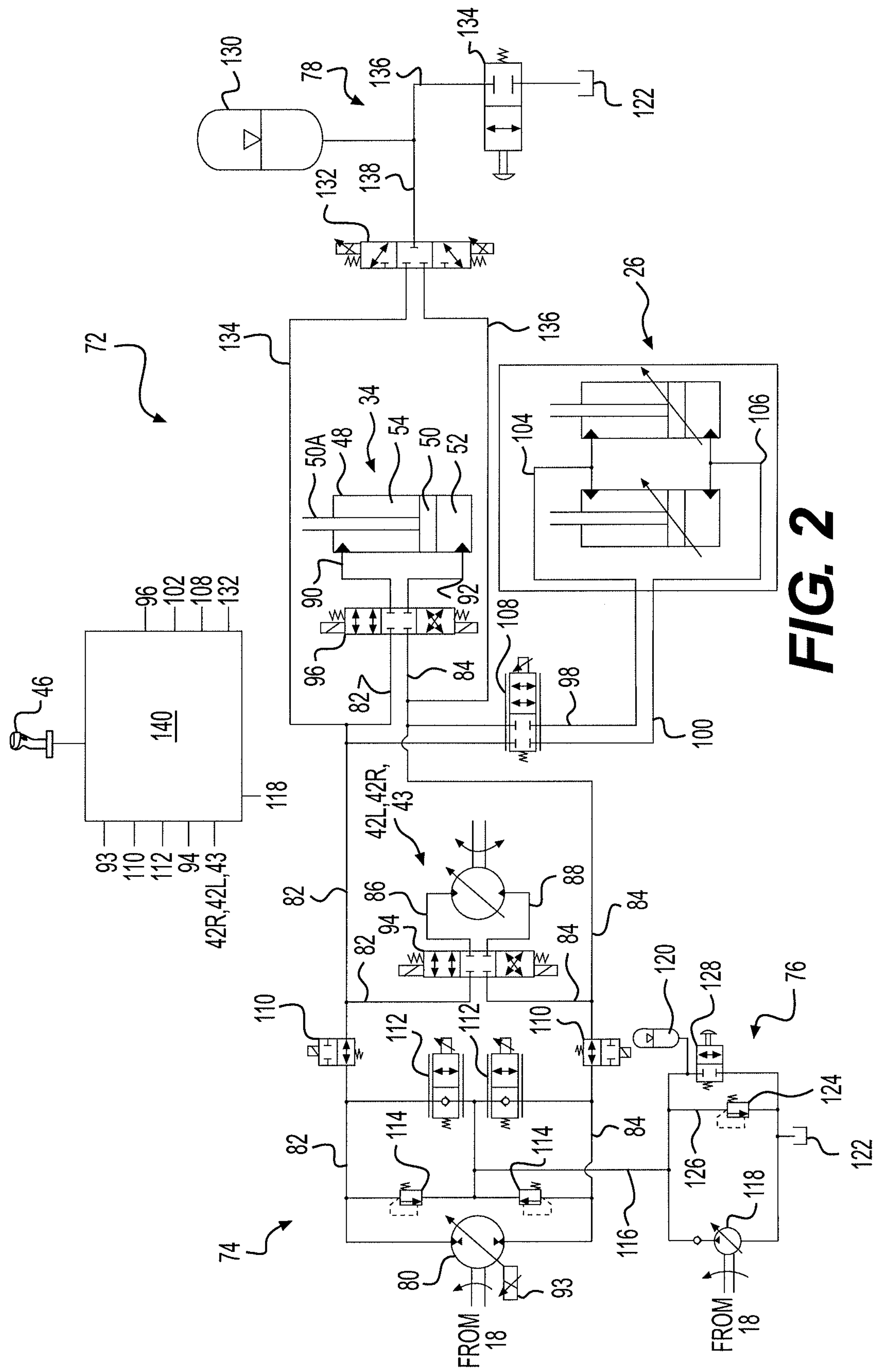

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FIG. 2

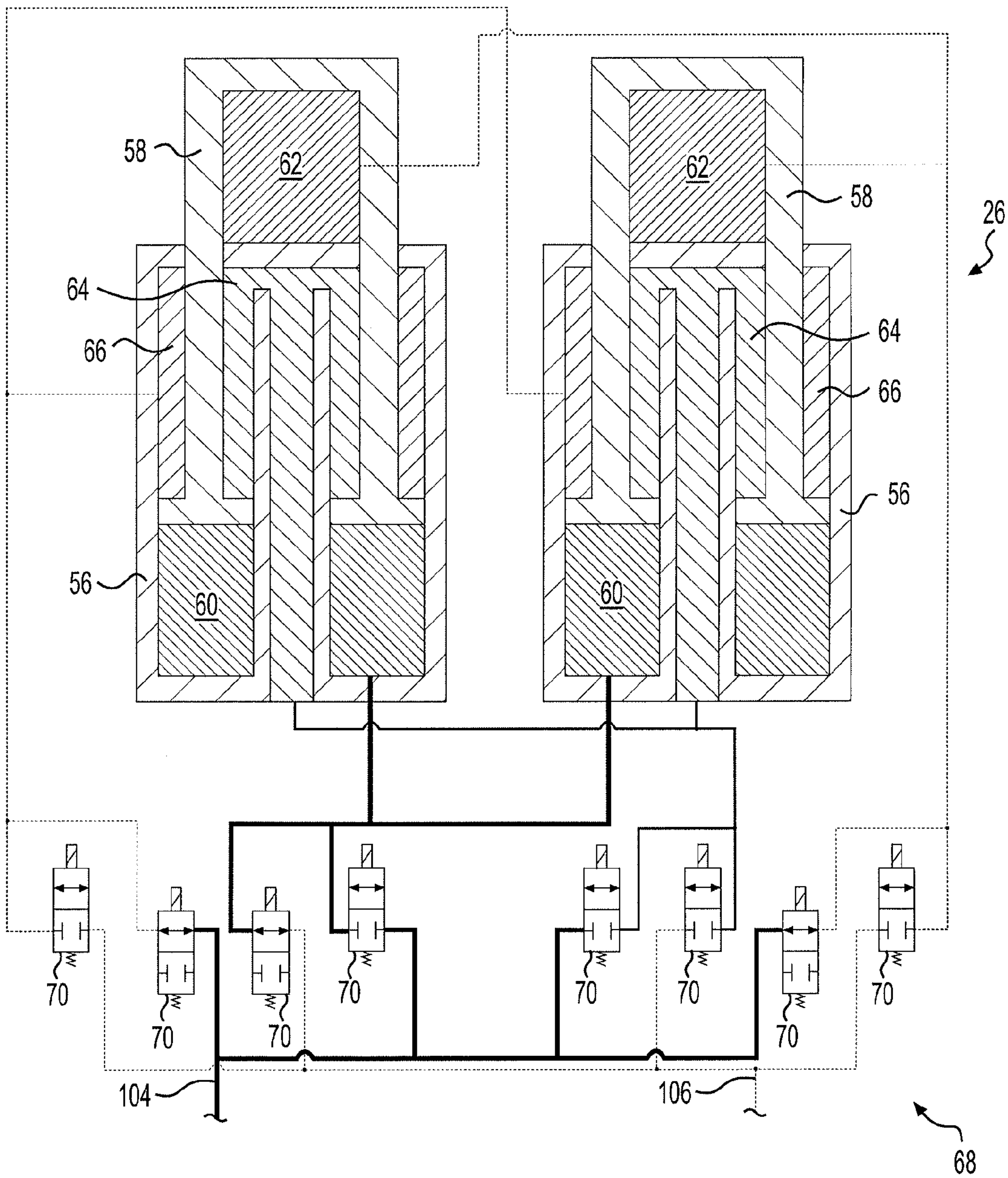
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FIG. 3

METERLESS HYDRAULIC SYSTEM HAVING MULTI-ACTUATOR CIRCUIT

TECHNICAL FIELD

The present disclosure relates generally to a hydraulic system and, more particularly, to a meterless hydraulic system having a multi-actuator circuit.

BACKGROUND

A conventional hydraulic system includes a pump that draws low-pressure fluid from a tank, pressurizes the fluid, and makes the pressurized fluid available to multiple different actuators for use in moving the actuators. In this arrangement, a speed of each actuator can be independently controlled by selectively throttling (i.e., restricting) a flow of the pressurized fluid from the pump into each actuator. For example, to move a particular actuator at a high speed, the flow of fluid from the pump into the actuator is restricted by only a small amount. In contrast, to move the same or another actuator at a low speed, the restriction placed on the flow of fluid is increased. Although adequate for many applications, the use of fluid restriction to control actuator speed can result in flow losses that reduce an overall efficiency of a hydraulic system.

An alternative type of hydraulic system is known as a meterless hydraulic system. A meterless hydraulic system generally includes a pump connected in closed-loop fashion to a single actuator or to a pair of actuators operating in tandem. During operation, the pump draws fluid from one chamber of the actuator(s) and discharges pressurized fluid to an opposing chamber of the same actuator(s). To move the actuator(s) at a higher speed, the pump discharges fluid at a faster rate. To move the actuator with a lower speed, the pump discharges the fluid at a slower rate. A meterless hydraulic system is generally more efficient than a conventional hydraulic system because the speed of the actuator(s) is controlled through pump operation as opposed to fluid restriction. That is, the pump is controlled to only discharge as much fluid as is necessary to move the actuator(s) at a desired speed, and no throttling of a fluid flow is required.

An exemplary meterless hydraulic system is disclosed in U.S. Pat. No. 4,369,625 of Izumi et al. (the '625 patent). In the '625 patent, a multi-actuator meterless-type hydraulic system is described that has flow combining functionality. The hydraulic system includes a swing circuit, a boom circuit, a stick circuit, a bucket circuit, a left travel circuit, and a right travel circuit. Each of the swing, boom, stick, and bucket circuits has a pump connected to a specialized actuator in a closed-loop manner. In addition, a first combining valve is connected between the swing and stick circuits, a second combining valve is connected between the stick and boom circuits, and a third combining valve is connected between the bucket and boom circuits. The left and right travel circuits are connected in parallel to the pumps of the bucket and boom circuits, respectively. In this configuration, any one pump can provide pressurized fluid to multiple different actuators in a closed-loop manner, thereby increasing functionality of the actuators while reducing a number of pumps necessary to drive the actuators.

Although an improvement over existing meterless hydraulic systems, the meterless hydraulic system of the '625 patent may still be less than optimal. In particular, because each actuator of the '625 patent may only be regulated via displacement control of the associated pump, any change in pump operation will simultaneously affect control of all

actuators connected to the same pump. Accordingly, the '625 patent may not provide a way to simultaneously move multiple actuators independently.

The hydraulic system of the present disclosure is directed toward solving one or more of the problems set forth above and/or other problems of the prior art.

SUMMARY

In one aspect, the present disclosure is directed to a hydraulic system. The hydraulic system may include a pump, a first actuator, and a meterless circuit connecting the first actuator to the pump. The hydraulic system may also include a second actuator connected to the meterless circuit in parallel with the first actuator. The second actuator may be a variable-area linear actuator.

In another aspect, the present disclosure is directed to a method of operating a hydraulic system. The method may include pressurizing fluid with a pump, directing fluid pressurized by the pump to a first linear actuator and returning fluid from the first linear actuator to the pump via a meterless circuit, and adjusting operation of the pump to adjust operation of the first linear actuator. The method may also include directing fluid pressurized by the pump to a second linear actuator and returning fluid from the second linear actuator to the pump via the meterless circuit, and adjusting a pressure area of the second linear actuator to adjust operation of the second actuator.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a pictorial illustration of an exemplary disclosed machine;

FIG. **2** is a schematic illustration of an exemplary disclosed hydraulic system that may be used in conjunction with the machine of FIG. **1**; and

FIG. **3** is a schematic illustration of an exemplary disclosed actuator configuration that may be used in conjunction with the hydraulic system of FIG. **2**.

DETAILED DESCRIPTION

FIG. **1** illustrates an exemplary machine **10** having multiple systems and components that cooperate to accomplish a task. Machine **10** may embody a fixed or mobile machine that performs some type of operation associated with an industry such as mining, construction, farming, transportation, or another industry known in the art. For example, machine **10** may be an earth moving machine such as an excavator (shown in FIG. **1**), a dozer, a loader, a backhoe, a motor grader, a dump truck, or another earth moving machine. Machine **10** may include an implement system **12** configured to move a work tool **14**, a drive system **16** for propelling machine **10**, a power source **18** that provides power to implement system **12** and drive system **16**, and an operator station **20** situated for manual control of implement system **12**, drive system **16**, and/or power source **18**.

Implement system **12** may include a linkage structure acted on by linear and rotary fluid actuators to move work tool **14**. For example, implement system **12** may include a boom **22** that is vertically pivotal about a horizontal axis (not shown) relative to a work surface **24** by a pair of adjacent, double-acting, hydraulic cylinders **26** (only one shown in FIG. **1**). Implement system **12** may also include a stick **28** that is vertically pivotal about a horizontal axis **30** by a single, double-acting, hydraulic cylinder **32**. Implement system **12** may further include a single, double-acting, hydraulic cylinder **34** that is operatively connected between stick **28** and work tool **14** to pivot work tool **14** vertically about a horizontal pivot axis **36**. In the disclosed embodiment, hydraulic cylinder **34** is connected at a head-end **34**A to a portion of stick **28** and at an opposing rod-end **34**B to work tool **14** by way of a power link **37**. Boom **22** may be pivotally connected to a body **38** of machine **10**. Body **38** may be connected to an undercarriage **39** to swing about a vertical axis **41** by a hydraulic swing motor **43**. Stick **28** may pivotally connect boom **22** to work tool **14** by way of axes **30** and **36**.

Numerous different work tools **14** may be attachable to a single machine **10** and operator controllable. Work tool **14** may include any device used to perform a particular task such as, for example, a bucket (shown in FIG. **1**), a fork arrangement, a blade, a shovel, a ripper, a dump bed, a broom, a snow blower, a propelling device, a cutting device, a grasping device, or any other task-performing device known in the art. Although connected in the embodiment of FIG. **1** to pivot in the vertical direction relative to body **38** of machine **10** and to swing in the horizontal direction, work tool **14** may alternatively or additionally rotate relative to stick **28**, slide, open and close, or move in any other manner known in the art.

Drive system **16** may include one or more traction devices powered to propel machine **10**. In the disclosed example, drive system **16** includes a left track **40**L located on one side of machine **10**, and a right track **40**R located on an opposing side of machine **10**. Left track **40**L may be driven by a left travel motor **42**L, while right track **40**R may be driven by a right travel motor **42**R. It is contemplated that drive system **16** could alternatively include traction devices other than tracks, such as wheels, belts, or other known traction devices. Machine **10** may be steered by generating a speed and/or rotational direction difference between left and right travel motors **42**L, **42**R, while straight travel may be facilitated by generating substantially equal output speeds and rotational directions from left and right travel motors **42**L, **42**R.

Power source **18** may embody an engine such as, for example, a diesel engine, a gasoline engine, a gaseous fuel-powered engine, or another type of combustion engine known in the art. It is contemplated that power source **18** may alternatively embody a non-combustion source of power such as a fuel cell, a power storage device, or another source known in the art. Power source **18** may produce a mechanical or electrical power output that may then be converted to hydraulic power for moving hydraulic cylinders **26**, **32**, **34** and left travel, right travel, and swing motors **42**L, **42**R, **43**.

Operator station **20** may include devices that receive input from a machine operator indicative of desired machine maneuvering. Specifically, operator station **20** may include one or more operator interface devices **46**, for example a joystick (shown in FIG. **1**), a steering wheel, or a pedal, that are located proximate an operator seat (not shown). Operator interface devices **46** may initiate movement of machine **10**, for example travel and/or tool movement, by producing displacement signals that are indicative of desired machine maneuvering. As an operator moves interface device **46**, the operator may affect a corresponding machine movement in a desired direction, with a desired speed, and/or with a desired force.

As shown in FIG. **2**, hydraulic cylinder **34** may include a tube **48** and a piston assembly **50** arranged within tube **48** to form a first chamber **52** and an opposing second chamber **54**. In one example, a rod portion **50**A of piston assembly **50** may extend through an end of second chamber **54**. As such, second chamber **54** may be considered the rod-end chamber of hydraulic cylinder **34**, while first chamber **52** may be considered the head-end chamber.

First and second chambers **52**, **54** may each be selectively supplied with pressurized fluid and drained of the pressurized fluid to cause piston assembly **50** to displace within tube **48**, thereby changing an effective length of hydraulic cylinder **34** and moving work tool **14** relative to stick **28** (referring to FIG. **1**). A flow rate of fluid into and out of first and second chambers **52**, **54** may relate to a translational velocity of hydraulic cylinder **34**, while a pressure differential between first and second chambers **52**, **54** may relate to a force imparted by hydraulic cylinder **34** on work tool **14**. It should be noted that hydraulic cylinder **34** may be a fixed-area linear actuator, wherein areas exposed to pressurized fluid within first and second chambers **52**, **54** of hydraulic cylinder **34** remain fixed throughout operation. Accordingly, for a given pressure differential across piston assembly **50**, a force generated by hydraulic cylinder **34** should remain relatively constant.

Although FIG. **2** only illustrates a single rotary actuator, it should be noted that the depicted rotary actuator may represent any one or more of left travel motor **42**L, right travel motor **42**R, and swing motor **43**. Each of left travel motor **42**L, right travel motor **42**R, and swing motor **43**, like hydraulic cylinder **34**, may be driven by a fluid pressure differential. Specifically, each rotary actuator may include first and second chambers (not shown) located to either side of a pumping mechanism such as an impeller, plunger, or series of pistons (not shown). When the first chamber is filled with pressurized fluid and the second chamber is drained of fluid, the pumping mechanism may be urged to rotate in a first direction. Conversely, when the first chamber is drained of fluid and the second chamber is filled with pressurized fluid, the pumping mechanism may be urged to rotate in an opposite direction. The flow rate of fluid into and out of the first and second chambers may determine a rotational velocity of the rotary actuator, while a pressure differential across the pumping mechanism may determine an output torque. It is contemplated that a displacement of any one or all of the rotary actuators may be variable, if desired, such that for a given flow rate and/or pressure of supplied fluid, a speed and/or torque output of a particular rotary actuator may be selectively and independently adjusted. In the disclosed embodiment, the rotary actuators are shown as unidirectional actuators, although over-center rotary actuators may also be utilized, if desired.

FIG. **2** illustrates only a symbolic representation of hydraulic cylinders **26** at an intended relative location, while FIG. **3** illustrates a detailed exemplary configuration of hydraulic cylinders **26**. As shown in FIG. **3**, hydraulic cylinders **26** may be variable-area linear actuators. That is, each of hydraulic cylinders **26** may include a greater number of pressure chambers than found in a typical hydraulic cylinder (e.g., more that found in hydraulic cylinder **34** shown in FIG. **2**), and each of these chambers may be selectively used to adjust operation of hydraulic cylinder **26**. For example, each of hydraulic cylinders **26** depicted in FIG. **3** includes a housing **56** and a piston assembly **58** that divides housing **56** into four different pressure chambers, including a first pressure chamber **60**, a second pressure chamber **62**, a third pressure chamber **64**, and a fourth pressure chamber **66**. First and second pressure chambers **60**, **62** may each include a pressure area that generates an extending force on hydraulic cylinder **26** when exposed to fluid having an elevated pressure. Similarly, third and fourth pressure chambers **64**, **66** may each include a pressure area that generates a retracting force on hydraulic cylinder **26** when exposed to fluid having an elevated pressure. Depending on the pressures of fluid introduced into each of these chambers **60**-**66**, hydraulic cylinders **26** may perform differently. For example, given a high-pressure source and a low-pressure source, pressure chambers **60-66** may each be selectively supplied with fluid at the high-pressure, fluid at the low-pressure, or fluid at a medium-pressure (e.g., a pressure attained by mixing fluid from the high- and low-pressure sources) to generate up to 16 discrete levels of force imparted by hydraulic cylinders **26** on boom **22** (referring to FIG. **1**).

As also shown in FIG. **3**, hydraulic cylinders **26** may be equipped with a valve arrangement **68** that provides for selective flow control of fluid from the high- and the low-pressure sources into the four pressure chambers **60-66** discussed above. In the disclosed embodiment, valve arrangement **68** includes eight independent on/off-type valves **70** (two valves **70** per pressure chamber, including one for high-pressure control and one for low-pressure control), each valve **70** being configured to move between a fully-open or flow-passing position and a fully-closed or flow-blocking position. Depending on the position of valves **70** paired for a particular one of pressure chambers **60-66**, each of pressure chambers **60-66** may be exposed to high-pressure fluid (by fully opening the high-pressure valve), low-pressure fluid (by fully opening the lower pressure valve), or medium-pressure fluid (by simultaneously opening both the low- and high-pressure valves). In addition, each of pressure chambers **60-66** may generate a corresponding force on hydraulic cylinder **26** alone, with, or against another one or more of pressure chambers **60**, **66**. It is contemplated that valve arrangement **68** may be integrally packaged with hydraulic cylinders **26** or packaged separately and fluidly connected to hydraulic cylinders **26** via external conduits, as desired.

It should be noted that a valve configuration other than arrangement **68** depicted in FIG. **3** may be utilized in conjunction with hydraulic cylinders **26**, if desired. For example, an arrangement having one or more spool valves that control simultaneous filling of one or more chambers from both the low- and high-pressure sources or a configuration utilizing variable position valves that meter fluid into and/or out of pressure chambers **60-66** may be utilized. A different valve configuration could result in a greater (e.g., infinite) or lesser number of force levels possible with hydraulic cylinders **26**. One skilled in the art will recognize, however, that fluid metering by valve arrangement **68** could reduce the efficiency of hydraulic cylinders **26**.

Although not shown, it is contemplated that hydraulic cylinder **32** (referring to FIG. **1**) may embody a fixed-area linear actuator similar to hydraulic cylinder **34** shown in FIG. **2**, or a variable-area linear actuator similar to hydraulic cylinders **26** shown in FIG. **3**. It is also contemplated that other actuators, for example auxiliary actuators, may be utilized within machine **10**, and embody rotary actuators similar to left travel, right travel or swing actuators **42**L, **42**R, **43**, or linear actuators similar to hydraulic cylinders **26** or **34**, as desired. For purposes of simplicity, hydraulic cylinder **32** is omitted from FIGS. **2** and **3**.

Returning to FIG. **2**, machine **10** may include a hydraulic system **72** having a plurality of fluid components that cooperate with the linear and rotary actuators described above to move work tool **14** (referring to FIG. **1**) and machine **10**. In particular, hydraulic system **72** may include, among other things, a meterless circuit **74** in communication with the different actuators of machine **10**, a charge circuit **76** in selective fluid communication with meterless circuit **74**, and an energy recuperation circuit **78** in selective fluid communication with meterless circuit **74**. It is contemplated that hydraulic system **72** may include additional and/or different circuits, if desired.

Meterless circuit **74** may include, among other things, a plurality of interconnecting and cooperating fluid components that facilitate the use and control of the associated actuators. For example, meterless circuit **74** may include a pump **80** fluidly connected to hydraulic cylinder **34** and rotary actuator(s) **42**L, **42**R, and/or **43** in a parallel, closed-loop manner via upper- and lower-side (relative to FIG. **2**) passages. Specifically, pump **80** may be connected to its rotary actuator(s) via a first pump passage **82**, a second pump passage **84**, and individual actuator passages **86**, **88**. In addition, pump **80** may be connected to hydraulic cylinder **34** via first and second pump passages **82**, **84**, a rod-end passage **90**, and a head-end passage **92**.

Pump **80** may have variable displacement and be controlled to draw fluid from its associated actuators and discharge the fluid at a specified elevated pressure back to the actuators in two different directions (i.e., pump **80** may be an over-center pump). Pump **80** may include a stroke-adjusting mechanism **93**, for example a swashplate, a position of which is hydro-mechanically adjusted based on, among other things, a desired speed of the actuators to thereby vary an output (e.g., a discharge rate) of pump **80**. The displacement of pump **80** may be adjusted from a zero displacement position at which substantially no fluid is discharged from pump **80**, to a maximum displacement position in a first direction at which fluid is discharged from pump **80** at a maximum rate into first pump passage **82**. Likewise, the displacement of pump **80** may be adjusted from the zero displacement position to a maximum displacement position in a second direction at which fluid is discharged from pump **80** at a maximum rate into second pump passage **84**. Pump **80** may be drivably connected to power source **18** of machine **10** by, for example, a countershaft, a belt, or in another suitable manner. Alternatively, pump **80** may be indirectly connected to power source **18** via a torque converter, a gear box, an electrical circuit, or in any other manner known in the art. It is contemplated that pump **80** may be connected to power source **18** in tandem (e.g., via the same shaft) or in parallel (e.g., via a gear train) with other pumps (not shown) of machine **10**, as desired.

Pump **80** may also be selectively operated as a motor. More specifically, when an associated actuator is operating in an overrunning condition (i.e., a condition where the actuator is driven by a load), the fluid discharged from the actuator may have a pressure elevated above an output pressure of pump **80**. In this situation, the elevated pressure of the actuator fluid directed back through pump **80** may function to drive pump **80** to rotate with or without assistance from power source **18**. Under some circumstances, pump **80** may even be capable of imparting energy to power source **18**, thereby improving an efficiency and/or capacity of power source **18**.

A first switching valve **94** may be disposed between first and second pump passages **82**, **84** and actuator passages **86**, **88**, while a second switching valve **96** may be disposed between first and second pump passages **82**, **84** and rod- and head-end passages **90**, **92**. In the depicted embodiment, switching valves **94**, **96** may be substantially identical, four-way, spool-type valves that are solenoid movable between three distinct position. When in the first position (shown in FIG. **2**), all fluid flow through switching valves **94**, **96**, may be substantially blocked. When in the second position (i.e., the upper position shown in FIG. **2**), switching valve **94** may connect first pump passage **82** to first actuator passage **86** and second pump passage **84** to second actuator passage **88**, and switching valve **96** may connect first pump passage **82** to rod-end passage **90** and second pump passage **82** to head-end passage **92**. When in the third position (i.e., the lower position shown in FIG. **2**), switching valve **94** may connect second pump passage **84** to first actuator passage **86** and first pump passage **82** to second actuator passage **88**, and switching valve **96** may connect second pump passage **84** to rod-end passage **90** and first pump passage **82** to head-end passage **90**. In this manner, a rotational/movement direction of the rotary actuator(s) and of hydraulic cylinder **34** may be switched either by switching an output flow direction of pump **80** and maintaining a current flow-passing position of switching valves **94**, **94**, or by maintaining the output flow direction of pump **80** and moving switching valves **94**, **96** between the second and third positions. The directions of the rotary actuator(s) and hydraulic cylinder **34** may be independently switched, if desired, through the use of only switching valves **94**, **96** or via a combination of pump displacement control and switching valve control. While switching valves **94**, **96** have been described as three-position, solenoid-operated valves, other types of valves (e.g., multiple independent on/off or metering type valves, valves have more or less than three positions, poppet-type valves, and other valves known in the art) may be utilized to switch fluid flow directions into the rotary actuator(s) and/or hydraulic cylinder **34**, if desired. If multiple rotary actuators are to be connected in parallel to meterless circuit **74**, each rotary actuator may have its own dedicated switching valve.

Hydraulic cylinders **26** may be connected to meterless circuit **74** in parallel with the rotary actuator(s) and hydraulic cylinder **34**. In particular, a first actuator passage **98** and a second actuator passage **100** may extend from first and second pump passages **82**, **84**, respectively, to rod- and head-end passages **104**, **106** that extend to hydraulic cylinder **26** (i.e., to valves **70** shown in FIG. **3**). In this configuration, first and second pump passages **82**, **84** may embody the low- and high-pressure sources discussed above with respect to FIG. **3**, depending on the output flow direction of pump **80**.

A combiner valve **108** may be disposed within first and second actuator passages **98**, **100** to selective fluidly communicate hydraulic cylinders **26** with meterless circuit **74**. In the disclosed embodiment, combiner valve **108** may have a valve element movable to any position between flow-blocking and flow-passing positions to selectively control a rate of fluid flow between meterless circuit **74** and hydraulic cylinders **26**. It is contemplated, however, that combiner valve **108** could alternatively embody a two-position (on/off) type of valve, if desired.

During some operations, it may be desirable to selectively isolate a suction or low-pressure side of pump **80** from the rotary actuator(s) and/or hydraulic cylinders **26**, **34**. For this purpose, meterless circuit **74** may be provided with isolation valves **110** capable of substantially blocking fluid flow from the rotary actuators and hydraulic cylinders **26**, **34** back to pump **80**. Isolation valves **110**, in the disclosed embodiment, may be on/off type valves that are solenoid-actuated toward a flow-blocking position and spring-biased toward a flow-passing position. When isolation valves **110** are in the flow-passing position, fluid may flow substantially unrestricted through meterless circuit **74** back into pump **80**. When isolation valves **110** are in the flow-blocking position, fluid may not return back to pump **80** from the rotary actuator(s) or hydraulic cylinders **26**, **34**.

It will be appreciated by those of skill in the art that the respective rates of hydraulic fluid flow into and out of the various pressure chambers of hydraulic cylinders **26**, **34** during extension and retraction may not be equal. For example, because of the location of rod portion **50**A within second chamber **54** of hydraulic cylinder **34**, piston assembly **50** may have a reduced pressure area within second chamber **54**, as compared with a pressure area within first chamber **52**. Accordingly, during retraction of hydraulic cylinder **34**, more hydraulic fluid may be forced out of first chamber **52** than can be consumed by second chamber **54** and, during extension, more hydraulic fluid may be consumed by first chamber **52** than is forced out of second chamber **54**. Similar situations may occur within the different pressure chambers **60**-**66** of hydraulic cylinders **26**. In order to accommodate the excess fluid discharged during retraction and the additional fluid required during extension, meterless circuit **74** may be provided with two makeup valves **112** and two relief valves **114** that connect first and second pump passages **82**, **84** to charge circuit **76** via a passage **116**.

Makeup valves **112** may each be a variable position valve that is disposed between passage **116** and one of first and second pump passages **82**, **84** and configured to selectively allow pressurized fluid from charge circuit **76** to enter first and second pump passages **82**, **84**. In particular, each of makeup valves **112** may be solenoid-actuated from a first position at which fluid freely flows between passage **116** and the respective first and second pump passage **82**, **84**, toward a second position at which fluid from passage **116** may flow only into first and second pump passage **82**, **84** when a pressure of passage **116** exceeds the pressure of first and second pump passages **82**, **84** by a threshold amount. Makeup valves **112** may be spring-biased toward their second positions, and only moved toward their first positions during operations known to have need of positive or negative makeup fluid. Makeup valves **112** may also be used to facilitate fluid regeneration between first and second pump passages **82**, **84**, by simultaneously moving together at least partway to their first positions.

Relief valves **114** may be provided to allow fluid relief from meterless circuit **74** into charge circuit **76** when a pressure of the fluid exceeds a set threshold of relief valves **114**. Relief valves **114** may be set to operate at relatively high pressure levels in order to prevent damage to hydraulic system **72**, for example at levels that may only be reached when the linear actuators (e.g., hydraulic cylinders **26**, **32**, **34**) reach an end-of-stroke position and the flow from pump **80** is non-zero, or during a failure condition of hydraulic system **72**.

Charge circuit **76** may include at least one hydraulic source fluidly connected to passage **116** described above. In the disclosed embodiment, charge circuit **76** has two sources, including a charge pump **118** and an accumulator **120**, which may be fluidly connected to passage **116** in parallel to provide makeup fluid to meterless circuit **74**. Charge pump **118** may embody, for example, an engine-driven, variable displacement pump configured to draw fluid from a tank **122**, pressurize the fluid, and discharge the fluid into passage **116**. Accumulator **120** may embody, for example, a compressed gas, membrane/spring, or bladder type of accumulator configured to accumulate pressurized fluid from and discharge pressurized fluid into passage **116**. Excess hydraulic fluid, either from charge pump **118** or from meterless circuit **74** (i.e., from operation of pump **80** and/or the rotary and linear actuators) may be directed into either accumulator **120** or into tank **122** by way of a charge relief valve **124** disposed in a return passage **126**. Charge relief valve **124** may be movable from a flow-blocking position toward a flow-passing position as a result of elevated fluid pressures within passages **116**, **126**. A manual service valve **128** may be associated with accumulator **120** to facilitate draining of accumulator **120** to tank **122** during service of charge circuit **76**.

Energy recuperation circuit **78** may include at least one high-pressure accumulator **130** that, depending on system demands, may be selectively connected to meterless circuit **74** via an accumulator valve **132** to either accumulate excess pressurized fluid or to discharge previously accumulated fluid. Accumulator **130** may be fluidly connected to first and second pump passages **82**, **84** via accumulator passages **134**, **136**, respectively, via accumulator valve **132**, and via a common passage **138**. Accumulator valve **132** may be a two-position (flow-blocking and flow-passing), solenoid-actuated valve that is configured to selectively control fluid flow between meterless circuit **74** and accumulator **130**. Accumulator valve **132** may be spring-biased toward the flow-blocking position. A manual service valve **135** may be associated with accumulator **130** to facilitate draining of accumulator **130** to tank **122** via a drain passage **137** during servicing.

During operation of machine **10**, the operator of machine **10** may utilize interface device **46** to provide a signal that identifies a desired movement of the various linear and/or rotary actuators to a controller **140**. Based upon one or more signals, including the signal from interface device **46** and, for example, signals from various pressure sensors (not shown) and/or position sensors (not shown) located throughout hydraulic system **72**, controller **140** may command movement of the different valves and/or displacement changes of the different pumps and motors to advance a particular one or more of the linear and/or rotary actuators to a desired position in a desired manner (i.e., at a desired speed and/or with a desired force).

Controller **140** may embody a single microprocessor or multiple microprocessors that include components for controlling operations of hydraulic system **72** based on input from an operator of machine **10** and based on sensed or other known operational parameters. Numerous commercially available microprocessors can be configured to perform the functions of controller **140**. It should be appreciated that controller **140** could readily be embodied in a general machine microprocessor capable of controlling numerous machine functions. Controller **140** may include a memory, a secondary storage device, a processor, and any other components for running an application. Various other circuits may be associated with controller **140** such as power supply circuitry, signal conditioning circuitry, solenoid driver circuitry, and other types of circuitry.

INDUSTRIAL APPLICABILITY

The disclosed hydraulic system may be applicable to any machine where improved hydraulic efficiency and performance are desired. The disclosed hydraulic system may provide for improved efficiency through the use of meterless technology. The disclosed hydraulic system may provide for an efficient, yet controllable, system through the use of a variable-area linear actuator. Operation of hydraulic system **72** will now be described.

During operation of machine **10**, an operator located within station **20** may command a particular motion of work tool **14** in a desired direction and at a desired velocity by way of interface device **46**. One or more corresponding signals generated by interface device **46** may be provided to controller **140** indicative of the desired motion, along with machine performance information, for example sensor data such a pressure data, position data, speed data, pump or motor displacement data, and other data known in the art.

In response to the signals from interface device **46** and based on the machine performance information, controller **140** may generate control signals directed to stroke adjusting mechanism **93** of pump **80**, to the rotary actuator(s), and to valves **94**, **96**, **108**, **110**, **112**, **132**. For example, to drive the rotary actuator(s) at an increasing speed in a first direction, controller **140** may generate a control signal that causes pump **80** of meterless circuit **74** to increase its displacement and discharge fluid into first pump passage **82** at a greater rate, while maintaining one of the second and third positions of first switching valve **94**. After fluid from pump **80** passes into and through the rotary actuator(s) via first pump passage **82**, the fluid may return to pump **80** via second pump passage **84**. To reverse the motion of the rotary actuator(s), the output direction of pump **80** may be reversed. If, during the motion of the rotary actuator(s), the pressure of fluid within either of first or second pump passages **82**, **84** becomes excessive (for example during an overrunning condition), fluid may be relieved from the pressurized passage to tank **122** via relief valves **114** and common passage **116**. Alternatively or additionally, the pressurized fluid may be directed into accumulator **130** via accumulator passages **134**, **136**, valve **132**, and common passage **138**. During charging of accumulator **130**, the suction or low-pressure side of pump **80** may be partially or fully blocked from the rotary actuator(s) via isolation valves **110**, such that the fluid discharging from the rotary actuator(s) may be forced into accumulator **130** rather than recirculated through meterless circuit **74**. In contrast, when the pressure of fluid within either of first or second pump passages **82**, **84** becomes too low, fluid from charge circuit **76** may be allowed into meterless circuit **74** via common passage **116** and makeup valves **112**.

During the motion of the rotary actuator(s), the operator may simultaneously request movement of hydraulic cylinder **34**. For example, the operator may request via interface device **46** that hydraulic cylinder **34** be retracted at an increasing speed. When this occurs, controller **140** may generate a control signal that causes pump **80** to increase its displacement and discharge fluid into first pump passage **82** at a greater rate. In addition, controller **140** may generate a control signal that causes second switching valve **96** to move toward and/or remain in its second position. As fluid from pump **80** passes into second chamber **54** of hydraulic cylinder **34** via first pump and rod-end passages **82**, **90**, fluid may be discharged from first chamber **52** back to pump **80** via head-end and second pump passages **92**, **84**.

The motion of hydraulic cylinder **34** may be reversed in two different ways. First, the operation of pump **80** may be reversed, thereby reversing the flows of fluid into and out of hydraulic cylinder **34**. Although satisfactory in some situations, this method of reversing cylinder motion may only be possible when first switching valve **94** is moved from the second position to the third position to also simultaneously reverse the rotational direction of the rotary actuator(s) (so as to maintain rotation in a desired constant direction) or when the rotary actuator(s) are already stopped and first switching valve **94** is in the flow-blocking position. Otherwise, the motion of hydraulic cylinder **34** may be reversed by moving second switching valve **96** to the third position. If, during the motion of hydraulic cylinder **34**, the pressure of fluid within either of first or second pump passages **82**, **84** becomes excessive (for example during an overrunning condition), fluid may be relieved from the pressurized passage to tank **122** via relief valves **114** and common passage **116**. Alternatively or additionally, the pressurized fluid may be directed into accumulator **130** via accumulator passages **134**, **136**, valve **132**, and common passage **138**. In contrast, when the fluid pressure becomes too low, fluid from charge circuit **76** may be allowed into meterless circuit **74** via common passage **116** and makeup valves **112**.

As described above, desired operation of the rotary and linear actuators may drive displacement control of pump **80**. When both rotary and linear actuator motion are simultaneously desired, however, directional displacement control of pump **80** may be driven based solely on the desired motion of only one of the linear and rotary actuators (e.g., based on the desired motion of hydraulic cylinder **34**), although the displacement magnitude of pump **80** may be based on flow requirements of both the rotary and linear actuators. At this time, in order to cause the rotary actuator(s) to independently move in a desired speed and/or with a desired torque, the displacement of the rotary actuator(s) may be selectively varied.

During the motion of the rotary actuator(s) and/or hydraulic cylinder **34**, the operator may simultaneously request movement of hydraulic cylinders **26**. For example, the operator may request via interface device **46** that hydraulic cylinders **26** be retracted at an increasing speed and/or with an increasing force. When this occurs, controller **140** may generate a control signal that causes pump **80** to increase its displacement and discharge fluid into first pump passage **82** at a greater rate. In addition, controller **140** may generate a control signal that causes valves **70** (referring to FIG. **3**) to communicate the fluid from pump **80** with pressure chambers **64** and/or **66**, depending on the desired level of speed and/or force. As fluid from pump **80** passes into pressure chambers **64** and/or **66** of hydraulic cylinders **26** via first pump and rod-end passages **82**, **104**, fluid may be discharged from pressure chambers **60** and/or **62** back to pump **80** via head-end and second pump passages **106**, **84**.

The motion of hydraulic cylinders **26** may be reversed in two different ways. First, the operation of pump **80** may be reversed, thereby reversing the flows of fluid into and out of hydraulic cylinders **26**. Although satisfactory in some situations, this method of reversing cylinder motion may only be possible when first and second switching valves **94**, **96** are moved from the second positions to the third positions (or vice versa) to also simultaneously reverse the rotational directions of the rotary actuator(s) and hydraulic cylinder **34** (so as to maintain rotation and translation in desired constant directions) or when the rotary actuator(s) and hydraulic cylinder **34** are already stopped and first and second switching valves **94**, **96** are in the flow-blocking positions. Otherwise, the motion of hydraulic cylinders **26** may be reversed by selectively opening and closing valves **70**.

As described above, hydraulic cylinders **26**, **34** may discharge more fluid during retracting operations than is consumed, and consume more fluid than is discharged during an extending operation. During these operations, accumulator valve **132** may be selectively opened to allow the excess fluid to enter and fill accumulator **130** (when the excess fluid has a sufficiently high pressure, for example during an overrunning condition) or to exit and replenish meterless circuit **74**, thereby providing a neutral balance of fluid entering and exiting pump **80**.

Regeneration of fluid may be possible when the pressure of fluid exiting an actuator is elevated above a discharge pressure of pump **80**. During this situation, both of makeup valves **112** may be simultaneously moved toward their flow-passing positions. In this configuration, makeup valves **112** may allow some of the fluid exiting the actuators to bypass pump **80** and flow directly back to the actuators. This operation may help to reduce a load on pump **80**, while still satisfying operator demands, thereby increasing an efficiency of machine **10**. In some embodiments, makeup valves **112** may be held partially closed during regeneration to facilitate some energy dissipation that improves controllability.

In the disclosed embodiment of hydraulic system **72**, fluid flows provided by pump **80** may be used by the associated linear and rotary actuators in a substantially unrestricted (i.e., unmetered) manner, such that significant energy is not unnecessarily wasted in the actuation process. Thus, embodiments of the disclosure may provide improved energy usage and conservation. In addition, the meterless operation of hydraulic system **72** may, in some applications, allow for a reduction or even complete elimination of metering valves for controlling fluid flow associated with the linear and rotary actuators. This reduction may result in a less complicated and/or less expensive system.

The disclosed hydraulic system may also provide for a reduction in the number of pumps required to facilitate meterless operation of multiple actuators, while still allowing independent and simultaneous control of the actuators. That is, through the use of switching valves, variable displacement rotary actuators, and a variable-area actuator, multiple different actuators can be simultaneously operated and provided with fluid pressurized by a common pump, while still maintaining independent control over each actuator. This ability may help to reduce the number of pumps required on machine **10**, along with the associated complexity and cost.

It will be apparent to those skilled in the art that various modifications and variations can be made to the disclosed hydraulic system. Other embodiments will be apparent to those skilled in the art from consideration of the specification and practice of the disclosed hydraulic system. It is intended that the specification and examples be considered as exemplary only, with a true scope being indicated by the following claims and their equivalents.

What is claimed is:

1. A hydraulic system, comprising:
- a pump;
- a first actuator, wherein the first actuator is a fixed-area linear actuator;
- a meterless circuit connecting the first actuator to the pump;
- a second actuator connected to the meterless circuit in parallel with the first actuator, the second actuator being a variable-area linear actuator;
- a rotary actuator connected to the meterless circuit in parallel with the first and second actuators; and
- at least a first switching valve associated with the rotary actuator and configured to switch a flow direction of fluid passing through the rotary actuator.

2. The hydraulic system of claim **1**, wherein the pump is an over-center, variable-displacement pump.

3. The hydraulic system of claim **1**, further including at least a second switching valve associated with the second actuator and configured to switch a flow direction of fluid passing into the second actuator.

4. The hydraulic system of claim **3**, further including at least a third switching valve associated with the first actuator and configured to switch a flow direction of fluid passing into the first actuator.

5. The hydraulic system of claim **3**, further including a combiner valve disposed between the pump and the second actuator, the combiner valve configured to selectively communicate the pump with the second actuator.

6. The hydraulic system of claim **1**, further including at least one isolation valve configured to selectively isolate a suction side of the pump from the meterless circuit.

7. The hydraulic system of claim **6**, further including a charge circuit in selective fluid communication with the meterless circuit.

8. The hydraulic system of claim **7**, further including:
- at least one relief valve disposed between the meterless circuit and the charge circuit; and
- at least one makeup valve disposed between the charge circuit and the meterless circuit.

9. The hydraulic system of claim **1**, further including:
- an accumulator; and

an accumulator valve configured to selectively communicate the accumulator with the meterless circuit.

10. The hydraulic system of claim **1**, wherein the meterless circuit is a closed-loop circuit.

11. A hydraulic system, comprising:

an over-center, variable-displacement pump;

a fixed-area linear actuator;

a meterless circuit connecting the fixed-area linear actuator to the pump, wherein operation of the fixed-area linear actuator is controlled via regulation of the pump;

a variable-area linear actuator connected to the meterless circuit in parallel with the fixed-area linear actuator;

a rotary actuator connected to the meterless circuit in parallel with the first and second actuators; and

at least a first switching valve associated with the rotary actuator and configured to switch a flow direction of fluid passing through the rotary actuator.

12. The hydraulic system of claim **11**, further including a variable displacement rotary actuator connected to the meterless circuit in parallel with the fixed- and variable area actuators.

13. A method of operating a hydraulic system, comprising:

pressurizing fluid with a pump;

directing fluid pressurized by the pump to a first linear actuator and returning fluid from the first linear actuator to the pump via a meterless circuit;

adjusting operation of the pump to adjust operation of the first linear actuator;

directing fluid pressurized by the pump to a second linear actuator and returning fluid from the second linear actuator to the pump via the meterless circuit;

adjusting a pressure area of the second linear actuator to adjust operation of the second actuator;

at least partially isolating a suction side of the pump from the meterless circuit;

selectively storing fluid discharged from the first or second linear actuators while the suction side of the pump is at least partially isolated from the meterless circuit; and

providing makeup fluid to the meterless circuit during the selective storing of fluid.

14. The method of claim **13**, further including adjusting a displacement position of the pump to switch a movement direction of the first linear actuator.

15. The method of claim **13**, further including directing fluid pressurized by the pump to a rotary actuator and returning fluid from the rotary actuator to the pump via the meterless circuit.

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